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GEC FERRANTI PIEZO VIBRATORY GYROSCOPE

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Summary

Prototypes of a piezo-electric vibratory angular rate transducer (gyroscope) (PVG) have been constructed and evaluated.

The construction is on the lines suggested by Burdess (reference 4). The sensitive element is a cylinder of radially poled piezo-electric ceramic. The cylinder is metallised inside and out, and the outer metallisation is divided into eight electrodes. The metallisation on the inside is earthed.

A phase locked loop, using two pairs of the electrodes, causes the cylinder to vibrate in one of its two fundamental, degenerate modes. In the presence of rotation, some of the vibration is coupled into the other mode. This can be detected, or suppressed with a closed-up technique and provides a measure of rotation rate.

Thy gyroscope provides a number of advantages over rotating mass and optical instruments: low size and mass, lower power consumption, potentially high reliability, potentially good dormancy, low cost and high maximum rate.

1. Introduction

The measurement of angular rate (relative to inertial space) is often a significant problem in spacecraft, (and other) system's development. Gyroscopes (angular rate sensors) are perceived as large, heavy, expensive, unreliable or some combination of these. Although the perception is not well-justified, the moves towards lighter space craft suggest that gyroscope technology is ripe for change.

There is a sizeable market (not confined to space craft) for gyros capable of measuring high angular rates, with a null accuracy of around a degree per second, and a scale factor accuracy of around one percent. Such instruments have to be cheap, small and robust. The GEC-Ferranti Piezo-Vibratory Gyro (PVG) is being developed for such a market. The target specification is reproduced below.

Parameter	Design Aim
Full scale rate	$\pm$100 deg/sec to $\pm$ 5000 deg/sec*
Full scale output	$\pm$ 10 volts d.c.
Over-Range	25,000 deg/sec
Excitation	$\pm$ 15 Volts d.c.
Power Consumption	1 Watt/axis
Null	$\pm$ 1 deg/sec after temperature consumption
Temperature Range	_ 40 deg. to + 80 deg. C
S/O to S/O Repeatability	<0.05 deg./sec
Hysteresis	<0.05 deg./sec
Resolution	<0.05 deg./sec
Threshold	<0.05 deg./sec
Linearity	0.25 % of Full Scale
Scale Factor	0.25 % after temperature compensation
Start-up Time	100 mS
Bandwidth	25Hz to 200Hz*
Noise	<0.04 [deg./sec]/$\sqrt{}$Hz
Size (in single-axis pack)	25mmϕ x 25mm long
Size of three axis pack	40mm cube max.

*Adjustable by change to electronics only.

Additionally, for a gyro of this type, low cost, high reliability, long operating time, and the capability of working in severe environment, are regarded as of particular importance.

2. Choice of technology

Traditionally, rotation sensors have been based on spinning wheels, but gyroscopes using either optical techniques and/or vibrating masses have become practical in recent years.

Existing spinning-mass gyros are unsuitable for this specification because of:-

(a) Cost: they are either expensive, or cost-cutting measures have unacceptable effects on lifetime or performance.

(b) Maximum rate: usually spinning-mass instruments cannot cope with more than (say) 100 degrees/second, and/or there is considerable increase in heat dissipation with rate.

Optical gyros are unlikely to meet the requirement because of both cost and size, although they are expected to do well in more demanding applications (e.g. better than 10 degrees/hour).

This leaves vibratory gyros, which have considerable potential, especially in terms of cost, size, weight, maximum rate, lifetime, bandwidth, power consumption and reliability.

3. Design Considerations in Vibratory Gyroscopes

There have been a number of attempts to develop vibratory gyros, dating back over the last thirty years. Examples include the Sperry "Gyrotron', RAE's experimental tuning-fork gyro, GE's vibrating beam gyro, and Honeywell's vibrating wire-gyro. The major problems with these devices, as far as we can tell, have been associated with the need to get the two resonant frequencies near identical, the need to prevent the vibration leaking away through the support, and various problems associated with the piezo-electric transducers which were bonded to metal vibrators.

The motion of any vibrating body is, in general, affected by the presence of rotation, through the Coriolis coupling [Reference 1]. The Coriolis effect depends on rotation rate, and therefore, in principle, any vibrating body can be used to detect rotation, i.e. as the basis of a gyroscope.

As an example, for educational purposes only, consider the vibrating cantilevered beam shown in Figure 1. The effect of the rotation is to introduce an out-of-plane vibration, as shown. This induced ['secondary'] vibration is at the same frequency as the primary vibration. Thus, to build such a gyro one would need a method of sustaining the primary vibration of the beam, and of detecting its out-of-plane [secondary] motion which is a direct measure of rotation rate. Both of these requirements can be met by pairs of piezo-electric transducers: one pair arranged to bend the beam and one pair to detect the strain in the other plane.

It is clear that to get a primary vibration of reasonable amplitude from the rather weak piezo-electric effect, one needs to make use of a mechanical resonance in the primary direction. To avoid difficulties with the resonant frequency variations [from component manufacturing tolerances or temperature, for example], it is necessary to incorporate the beam itself into the oscillator as the frequency-determining component. Similarly, it is clear that the secondary must be operated on resonance, and thus ideally one should have the two resonances at the same frequency. In practice, the frequency split between the two resonances needs to be rather smaller than the width of the resonances.
As the mechanical resonator is the frequency-determining part of the oscillator, it is desirable to have a resonator with a high Q factor. This situation gives a rapid change of phase with frequency, and thus a stable oscillator with little phase noise. Of course, to get a high Q factor, it is necessary to minimise the losses: in this case the power lost as vibration leaking out of the gyro. [A further reason for minimising the energy loss from the gyro is to reduce the risk of the cross-talk between the gyros].

In the educational example given above, one would expect therefore a gyro with that particular configuration would be unsuccessful. However, there are several better possibilities, including tuning forks, H-shapes and cylinder.

4. Description of the GEC-Ferranti Piezo-Electric Vibratory Gyro

GEC-Ferranti at Silverknowes, Edinburgh in Scotland, has been developing a vibratory gyro for around 3 years. The initial phase included a study of possible configurations and a tolerancing study.

An early decision was to avoid problems with bonding piezo-electric transducers to a metal resonator, by making the resonator itself from piezo-electric material, and by plating metal electrodes onto it. For each configuration considered, the possible materials and the directions of the piezo-electric properties, were considered. The outcome of this study was the decision to work primarily on a cylindrical configuration, with one open end and one closed end. The support was to be at the node at the centre of the closed end. As the cylinder's piezo-electric properties have to be cylindrically symmetric materials which are naturally piezo--electric cannot be used. Instead, we have been working with the sintered piezo-electric ceramic, which can be radially poled. [The material is sold under various names including "PZT"]

Once the ceramic cylinder has been ground to the correct dimensions, it is plated with metal on both the inside and outside, The outside plating is divided up into eight electrodes, which cover virtually all the area, but which are divided by small earthed strips. The metal on the inside is earthed. Figure 2[a] illustrates the configuration.

Several authors have described how such a configuration can be used as a gyro [reference 2]. A cylinder has, of course, a large number of natural modes, but most of these are unsuitable for use in the gyro. Figure 2[b] illustrates the primary mode excited, and the secondary mode detected, in the GEC-Ferranti gyro.

Before we started work on a cylinder gyro, Burdess had already patented [Reference 3] and published [Reference 4] the idea of the cylindrical vibratory gyroscope in piezo-electric ceramic and the ownership of the patent was with the British Technology Group [BTG]. GEC-Ferranti has made a licensing arrangement with BTG.

This cylinder gyroscope has much in common with the one described by Harris [Reference 5]. The major difference between that device and the Ferranti one is that in the former one the piezo-electric transducers are bonded onto the resonator, but in the GEC-Ferranti device the piezo-electric material is the resonator.

There are a number of advantages with the GEC-Ferranti arrangement, mainly to do with its simplicity, and hence its reliability. If a metal cylinder is used, piezo-electric elements have to be bonded onto the cylinder, and wires taken from them, near the point of maximum vibration. By contrast, there is no bonding to the vibrating part of the piezo-electric cylinder: the electrical connections can be made near the node.

Further advantages come from the fact that, in the piezo-electric cylinder, the electrodes are positioned by dividing up the plating, and this position can be trimmed later by removing more metal. This process is potentially more accurate than ones involving bonding the piezo-electric elements in place with adhesives.

The motion of the cylinder is too small and too fast to be seen by normal techniques, but it can be investigated by interferometric holography [Reference 6]. Such a technique gives a photograph of a fringe pattern, with the fringes being contours of equal vibration amplitude. Figure 3 is a line drawing traces from such an interferogram, showing the vibration node, and antinodes of around 1200 nm peak-to-peak.

5. Electronics

A block diagram of the gyro electronics is given in Figure 4. It can be divided into two areas

(a) Primary drive circuit
(b) Secondary detection and output circuit

The primary drive circuit is required to establish and sustain the cylinder's fundamental mode of vibration. This is achieved by using the resonant characteristics of the cylinder as the frequency selective parameters of a phase-locked, amplitude-stabilised oscillator. This configuration ensures fundamental-mode operation over a wide temperature range, since the cylinder's temperature-sensitive parameters are automatically compensated for.

As the rotation-induced secondary vibration is in phase with the primary vibration, it is possible simply to demodulate the output from any secondary electrode pair, with respect to the primary vibration, and to use this as the gyro output. However this 'open-loop' detection system is inherently non-linear.

To give an output which is linear with applied rate, a closed-loop secondary system is used. This system acts as a null-seeking servo, which suppresses the secondary vibration by applying a feedback-derived voltage to the secondary drive electrodes. This voltage is a linear function of applied rate.

6. Some results obtained with prototypes

To date, prototype PVGs have been characterised over $\pm$ 1000 degrees/second [scale factor of 10mV/[degree/second]], or over $\pm$ 100 degree/second [scale factor 100mV [degree/second]]. Examples of the results of rate tests are given in Figures 5 and 6. In each case the upper figure gives the output voltage as a function of input rate, and the lower figure the deviation of the data from the best straight line. The lower plots are over the range ±0.5% of full rate. For the ±100 degree/second data, the worst deviation is 0.1% full scale, and the errors seem randomly distributed. For ±1000 degree/second data, the worst deviation is 0.3% full scale. There is a systematic element to this error, and we believe we understand the nature of the constructional inaccuracies which lead to this. Even so, the r.m.s. non-linearity is only 0.15% full scale.

Figure 7 shows the in-run drift of the gyro on a static overnight run. A simple model has been used to eliminate temperature effects. The data all lies within ±0.02 o/sec (±72^{o}/hour)

Figure 8 shows the variation of scale factor with temperature. Although the actual variation is rather large, the effect has good linearity, and there is every prospect that the temperature effect can be cancelled out.

References

1. 'Dynamics' by F.P. Beer and E.R. Johnston
   McGraw-Hill, pp 621-612

2. C.H.J. Fox
   DGON Gyro Symposium 1988, Paper 5

3. UK Patent BG 2 154 739 B

4. J.S. Burdess, Proc I Mech E Vol 200 (C4), pp 271-280 and UK Patent GB 2154739B

5 D.G. Harris, DGON Gyro Symposium 1988, Paper 6

6. R.J. Parker and D.G. Jones, Optical Engineering Vol 27 [1], January 1988

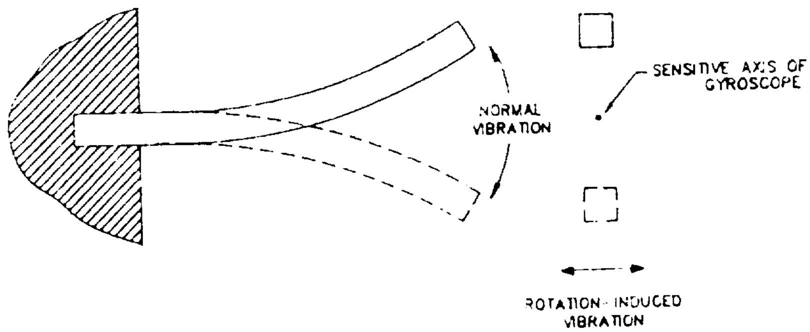


Figure 1

A hypothetical vibrating-beam gyroscope illustrating the principles of all vibratory gyros. The beam is caused to vibrate at its resonant frequency. The figure shows two views of the system with the solid and hatched beams representing the two extremes of the vibration. Rotation about the axis shown induces an out-of-plane vibration as indicated in the diagram.

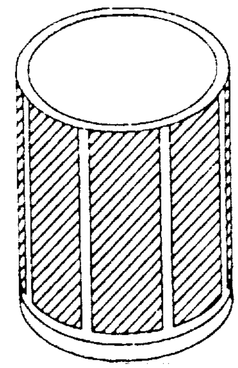


Figure 2a

The GEC-Ferranti Piezo-Electric Vibratory Gyro, showing the vibrating cylinder, made from piezo-electric material, and also the plated electrodes whose position is denoted by the hatched areas.

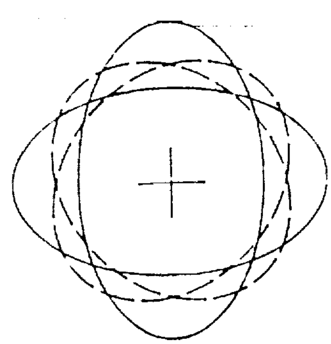


Figure 2b

The modes in a cylinder gyroscope. The primary mode comprises oscillation between the two solid ellipses. The secondary [rotation induced] mode is an oscillation between the two dashed ellipses.

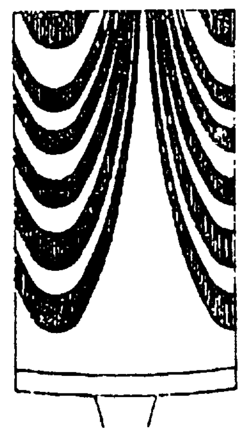


Figure 3

Laser interferogram of the vibratory cylinder. The fringes are lines of constant amplitude. [This is a line drawing produced from the interferogram].

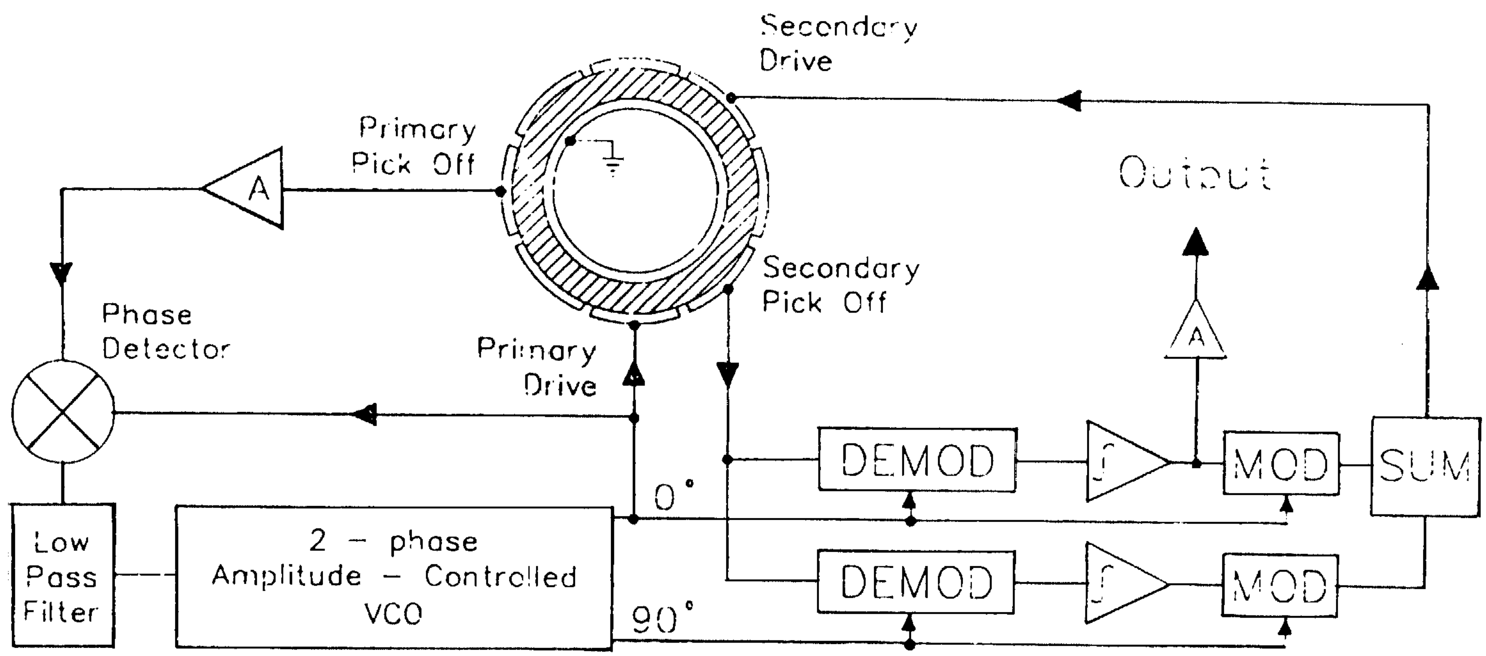


Figure 4

PVG Electronics.
Note that each electrode is connected in parallel with the one opposite.

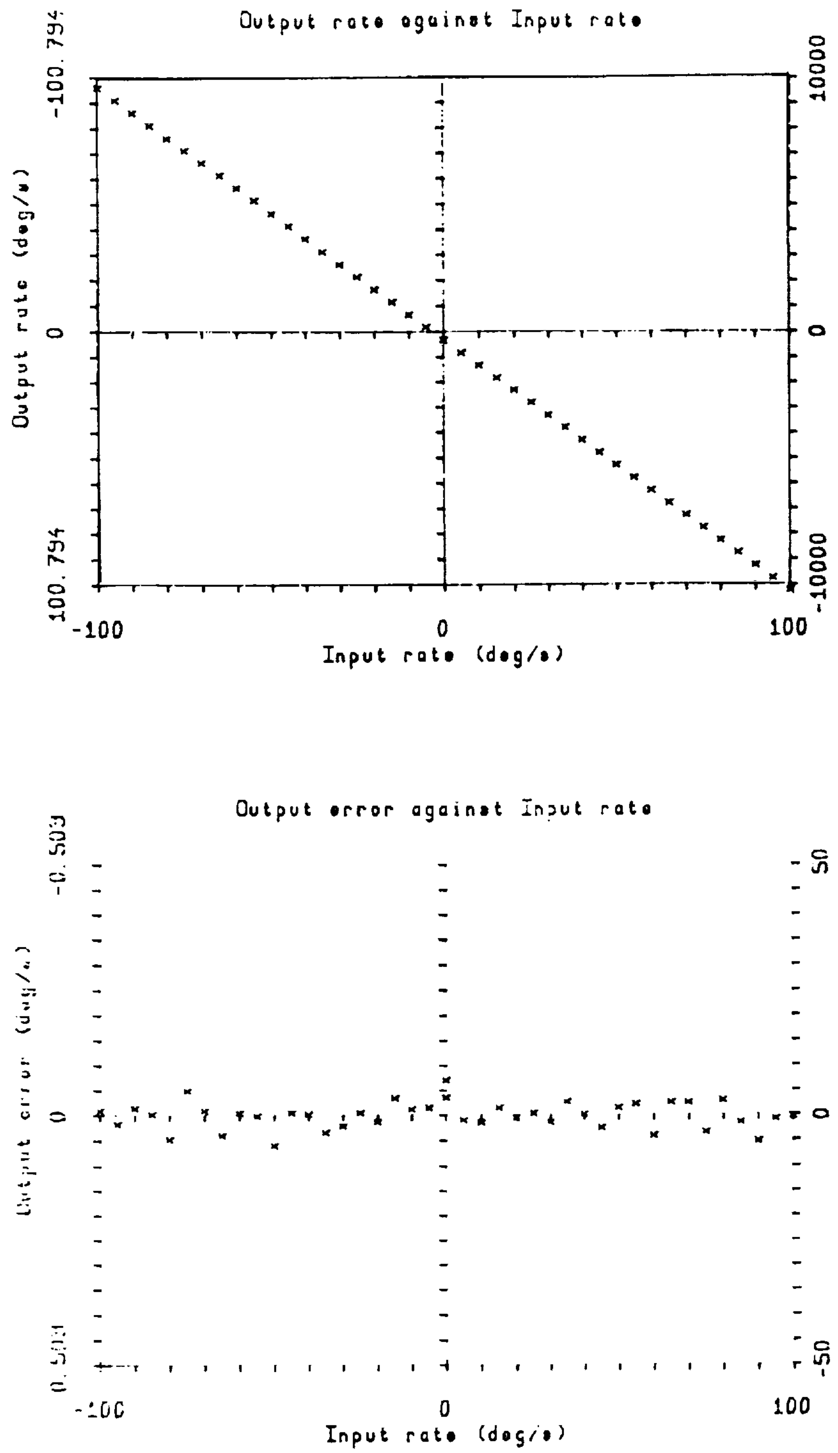
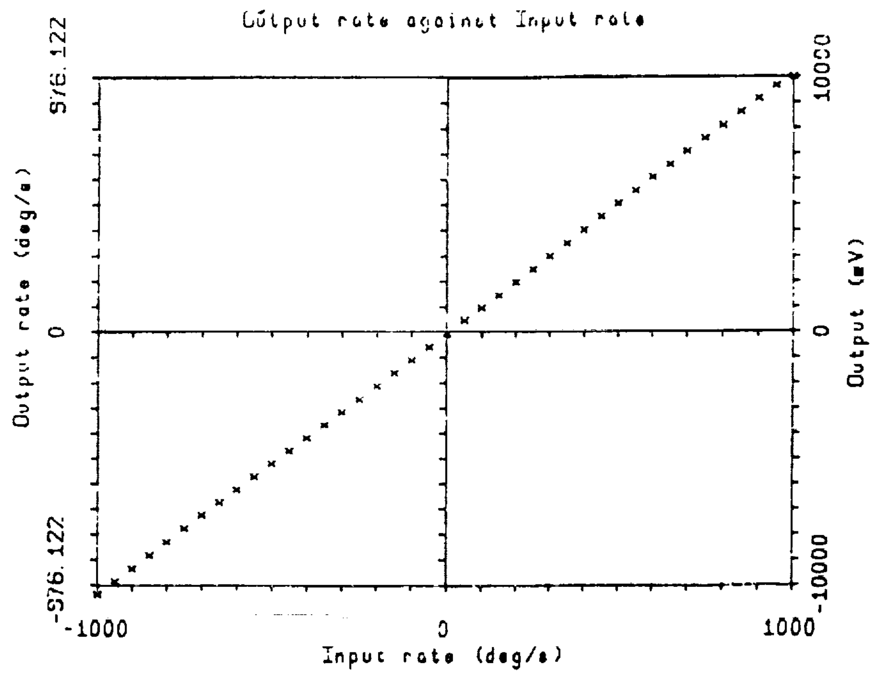
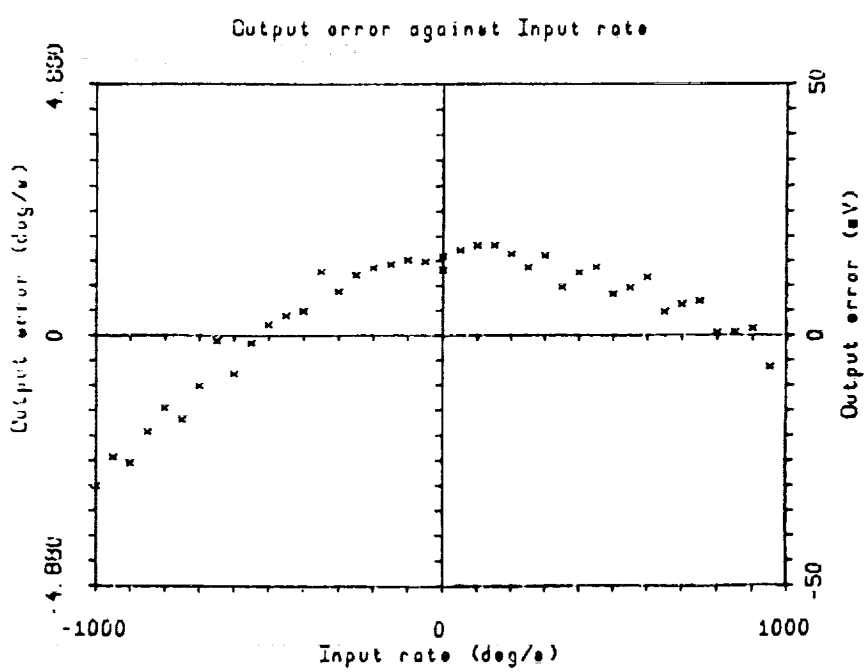


Figure 5

Result of rate test over ± 1000 degrees/second on GEC Ferranti Piezo Vibratory Gyro





<u>Figure 6</u>

Result of rate test over ± 1000 degree/second on GEC Ferranti Piezo Vibratory Gyro

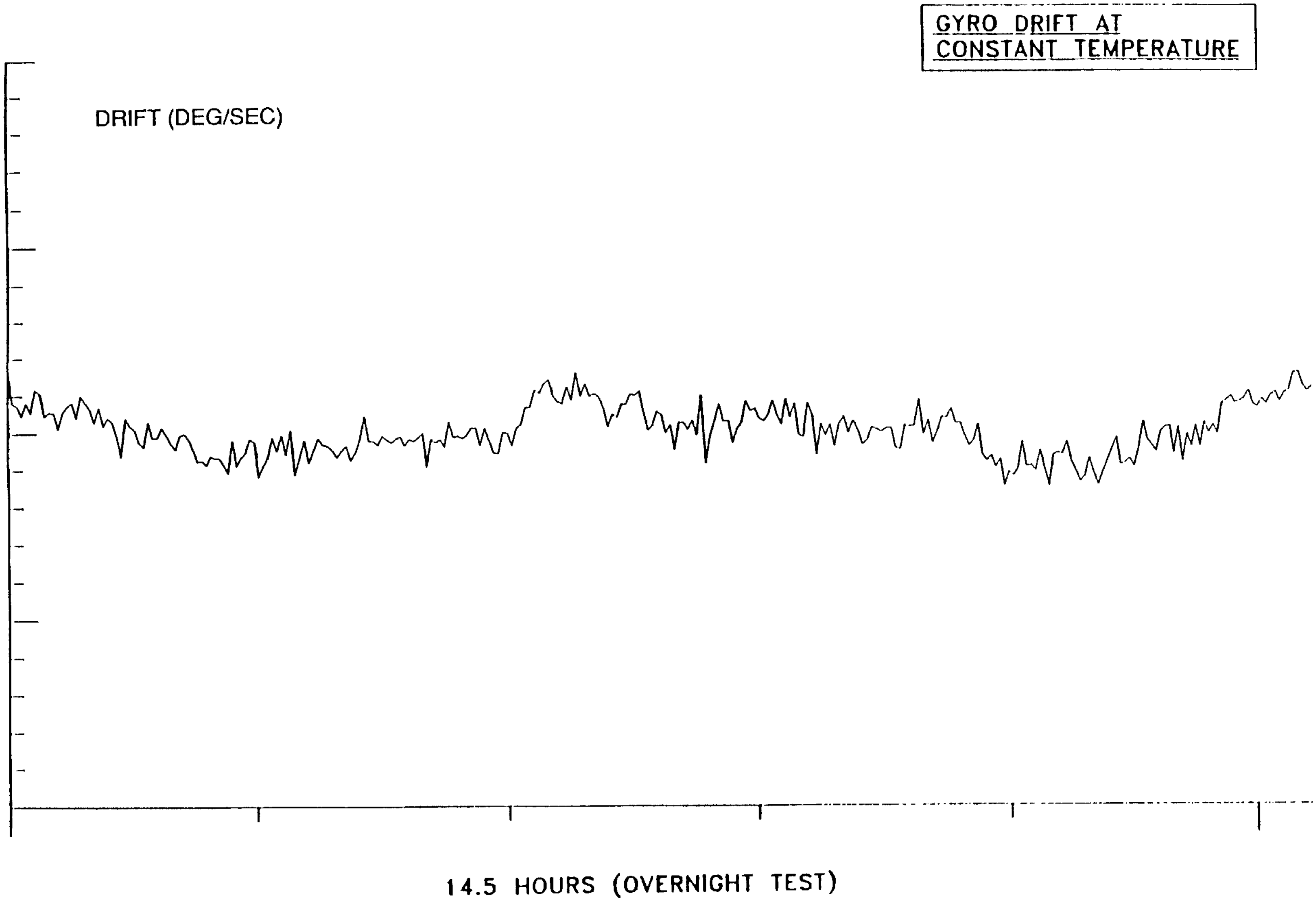


Figure 7

Result of drift test on GEC Ferranti Piezo Vibratory Gyro

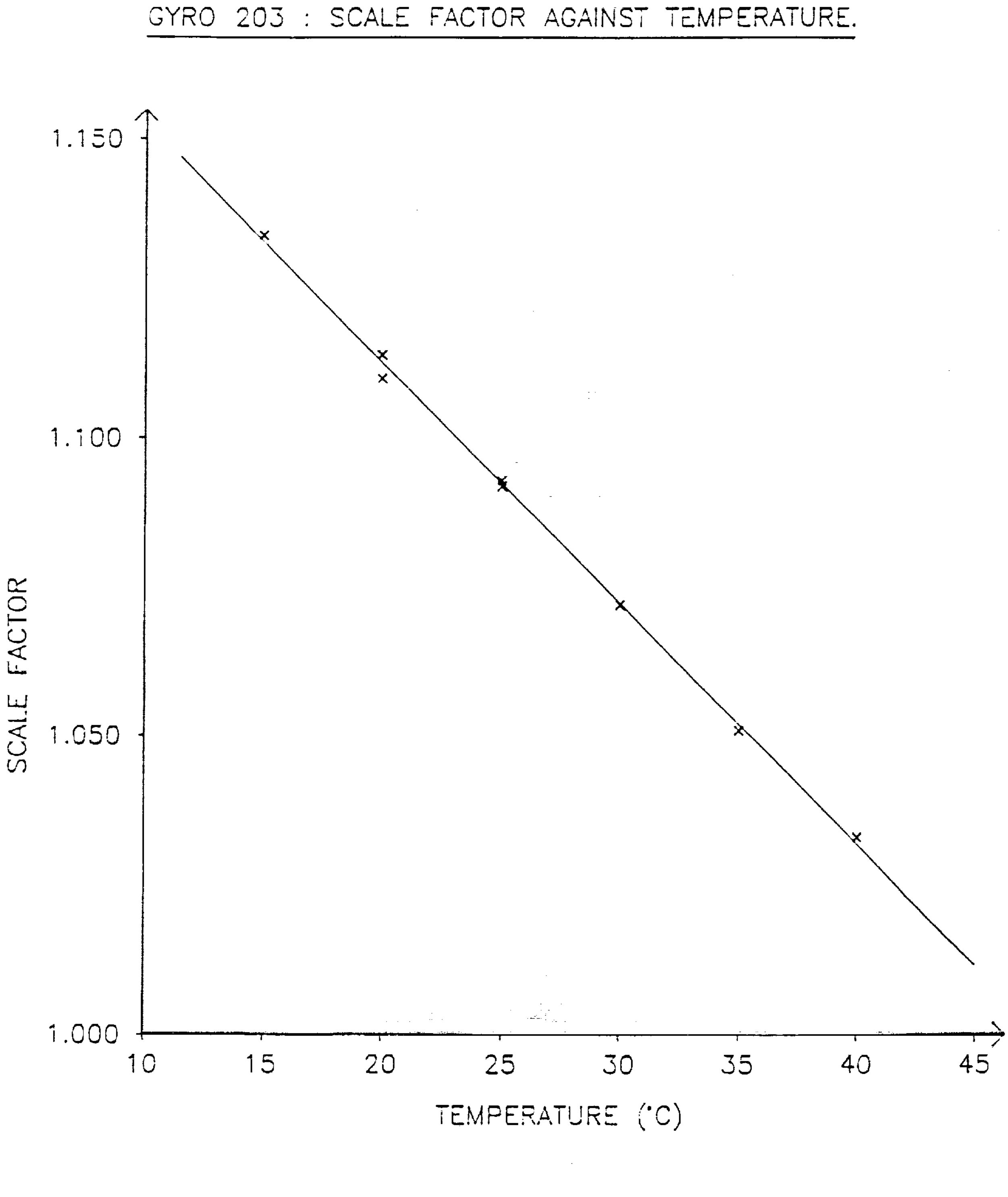


Figure 8

Results of a scale factor temperature sensitivity test on a GEC Ferranti Piezo Vibratory Gyro